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A Hubble Space Telescope Survey of X-ray Luminous Galaxy Clusters: Gravitationally Lensed Arcs and EROs

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Abstract. We are conducting a systematic lensing survey of X-ray luminous galaxy clusters at $z \sim 0.2$ using the *Hubble Space Telescope (HST)* and large ground-based telescopes. We summarize initial results from our survey, including a measurement of the inner slope of the mass profile of A 383, and a search for gravitationally lensed Extremely Red Objects.

1. Introduction

Gravitational lensing by galaxy clusters is a powerful tool for studying the distribution of mass in galaxy clusters at $z > 0.2$ (e.g. Kneib et al. 1996 – K96; Smith et al. 2001a – S01a) and the properties of high-redshift ($z \sim 1$–6) galaxies (e.g. Smith et al. 2002a – S02a; Smail et al. 2001; Ellis et al. 2001). For this reason, significant effort was invested during the 1990's in developing the lens inversion techniques required to interpret robustly cluster lensing observations (K96). During this period cluster lensing studies necessarily concentrated on a small number of well studied clusters.

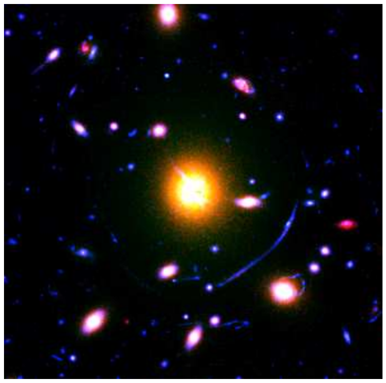
Our survey builds on the pioneering work of the 1990's and applies the K96 lens inversion technique to an objectively selected sample of clusters. Ideally we would select our cluster sample based on direct measurements of their mass. However, in the absence of large scale weak lensing surveys, we rely on X-ray luminosity as a crude indicator of cluster mass for the purpose of sample selection. We therefore select 12 X-ray luminous clusters ($L_{\rm X} \geq 8 \times 10^{44}\,{\rm erg\,s^{-1}}$, 0.1–2.4 keV) in a narrow redshift slice at $z = 0.17$–0.26, with line of sight reddening of $E(B-V) \leq 0.1$ from the XBACs sample (Ebeling et al. 1996).

We describe the first three published results from our survey: detailed modeling of the density profile of A 383 (S01a); a search for gravitationally lensed Extremely Red Objects (EROs) (S02a); and near-infrared (NIR) spectroscopy of a dusty ERO uncovered in S02a's survey (Smith et al. 2001b – S01b).

2. The Distribution of Matter in the Core ($r \lesssim 20$kpc) of Abell 383

A 383 was one of the first clusters to be observed by *HST* as part of our survey, revealing numerous previously unidentified multiple images including a "giant" tangential arc and two radial arcs (Fig. 1 & S01a). Such radial arcs are extremely rare and provide a unique opportunity to measure the slope of the cluster density

profile, in contrast to tangential arcs which are much more common and simply constrain the mass enclosed by the arc.



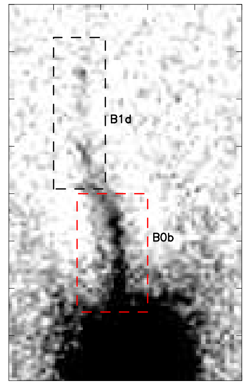


FIGURE 1. – Left: The central $\sim 50'' \times 50''$ of A 383, combining our WFPC2/F702W frame with K–band data from UKIRT (see §3). The large blue arc below-right of the image-centre is a "giant arc" consisting of several images of the same background galaxy, including one spectroscopically confirmed to lie at $z = 1.01$. The radial arcs (see text) lie in the very centre of the cluster and are hidden by the cluster cD galaxy in this frame. Right: The radial arcs in A 383, as seen with *HST* enhanced by subtracting a median-smoothed frame from the science frame. The bright emission at the bottom of this frame is the residual light from the cD galaxy after subtracting off the smoothed frame. Each tick mark represents $1''$.

Keck spectroscopy of the brightest feature of the giant arc reveals it to be an image of a star forming galaxy at $z = 1.01$. We use this spectroscopic redshift to calibrate a model of the mass distribution in this cluster and then investigate the slope of the cluster density profile using the radial arcs. Specifically, we investigate the degeneracy between the various model parameters that describe the cluster-scale dark matter halo and the central galaxy in this cluster. We conclude that a central galaxy mass component is required to explain the lensing properties of the cluster and that the de-projected slope of the inner region of the density profile ($10 \lesssim r \lesssim 50$kpc) is $\alpha = -1.30 \pm 0.04$ where $\rho \propto r^{\alpha}$. The central slope of A 383's density profile therefore appears to be intermediate between the predictions of Navarro, Frenk & White (1997) ($\alpha = -1$) and the higher resolution simulations of Ghigna et al. (1999) ($\alpha = -1.6 \pm 0.1$) (S01a).

Future analysis of A 383 will fully map the systematic uncertainties in our lens model, including those arising from the adoption of different parametrized mass profiles. We are also constructing lens models for the other clusters in our sample, and will study the sub-structure and correlations between cluster properties e.g. L_X, T_X and mass (Smith et al. 2002b). In conjunction with ongoing *XMM-Newton* observations, this will be a powerful dataset with which to quantify the distribution of matter in massive clusters at $z \sim 0.2$.

3. The Surface Density of Extremely Red Objects at $K \lesssim 22$

We also use these clusters as "gravitational telescopes" to investigate properties of distant galaxies. In particular we probe the formation epoch of massive elliptical galaxies. Photometrically selected evolved galaxies at $z > 1$ are a promising tool with which to tackle this issue. However, the definition of this population

(Extremely Red Objects – EROs) in terms of a simple optical/NIR color selection criterion (e.g. $(R-K)\geq 5.3$) produces a heterogeneous sample of galaxies, containing both active, dusty systems (e.g. Dey et al. 1999) and passive elliptical galaxies (e.g. Soifer et al. 1999). Attempts to study EROs in a systematic manner and so disentangle this mixture have also been severely hampered by their intrinsic faintness ($R \gtrsim 23$, $K \gtrsim 18$).

Our survey overcomes this problem, exploiting the magnifying power of massive galaxy cluster lenses to enhance the sensitivity of the observations (S02a). We combine our optical HST data (§2) with deep ground-based NIR data and construct a sample of 60 gravitationally lensed EROs with $(R-K) \geq 5.3$ (26 which have $(R-K) \geq 6.0$) down to $K \sim 22$ in the source plane (Fig. 2).

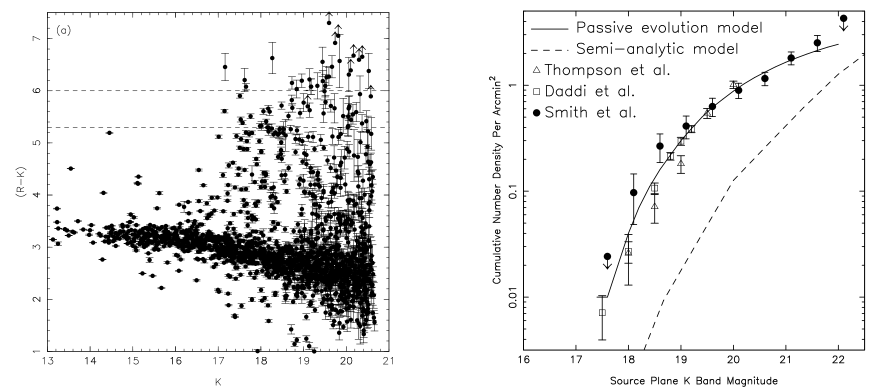


FIGURE 2. – Left: Composite $(R-K)$–K color-magnitude diagram for the ten cluster fields used in our search for gravitationally lensed EROs (S02a). Selection criteria of $(R-K) \geq 5.3$ and $(R-K) \geq 6.0$ are indicated by dashed lines. Right: Number counts of EROs with $(R-K) \geq 5.3$ after correcting for gravitational lensing. The surface density at $K \leq 21.6$ is 2.5 ± 0.4 arcmin^{-2}. The slope of the number counts changes at $K \sim 19.5$ (see text).

We use detailed lens models (K96, S01a, S02b) to correct our ERO sample for gravitational amplification (S02a), and show the corrected surface density of EROs in Fig. 2. These results agree with recent wide-field surveys ($K \lesssim 19.5$), but reveal a shallower slope at $K \gtrsim 19.5$. Together with color and morphological information, we interpret this as indicating that EROs are dominated by elliptical galaxies at $K \lesssim 19.5$, and are dominated by dusty systems at $K \gtrsim 19.5$.

We also compare our number counts with Cole et al.'s (2000 – C00) semi-analytic model of galaxy formation (Fig. 2). C00 use a well motivated prescription of galaxy formation physics to reproduce many of the properties of the local galaxy population (e.g. local K–band luminosity function). Despite success at low-redshift, C00 under-predict the observed ERO counts by approximately an order of magnitude (Fig. 2). This deficit of EROs implies that C00's model produces insufficient stars and/or dust in the early Universe.

Our future program will test S02a's hypothesis that the break in the ERO number counts is caused by a transition in the nature of EROs at $K \sim 19.5$.

4. ERO J164023 – A Dusty Starburst-Seyfert Galaxy at $z = 1.05$

We are also undertaking a program of NIR spectroscopy of our ERO sample. Observations with NIRSPEC on Keck-II (S01b) reveal that ERO J164023 ($K =$

17.6, $(R-K)=5.9$) is a dusty disk galaxy at $z=1.05$. S01b estimate that this galaxy suffers extinction of $A_V\sim 5$, suggesting that it may be similar to HR10 (Dey et al. 1999), one of only two other dusty EROs for which NIR spectroscopy is available. However, unlike HR10, this galaxy displays evidence (anomalous Hα/[NII] line ratio) of weak nuclear activity, indicating that this may be a composite starburst-Seyfert system. Dust-reddened EROs therefore appear to include composite systems (S01b) in addition to the starburst (Dey et al. 1999) and AGN (Pierre et al. 2001) systems that were previously known.

5. Summary

We are conducting a survey of 12 X-ray luminous galaxy clusters at $z\sim 0.2$ with *HST* and large ground-based telescopes. One of these clusters, A 383, contains two radial arcs which are used to constrain the inner slope of the cluster density profile (S01a). We find that the cluster scale dark matter halo appears to possess a central cusp. However, the logarithmic slope of this cusp is not well reproduced by either of the rival theoretical predictions of dark matter density profiles. S02a also exploit the magnifying power of our cluster lens sample to construct a sample of 60 gravitationally lensed EROs as faint as $K\sim 22$. Comparison of our observed ERO number counts with predictions from C00's semi-analytic model of galaxy formation reveals that this models under-predicts the observed ERO number counts by an order of magnitude. NIR spectroscopy reveals that one ERO in our sample is a dusty starburst-Seyfert galaxy at $z=1.05$ (S01b).

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